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16. ABSTRACT

Distribution system reliability for most utilities is maintained by the knowledge of a few key personnel. Generally, these water treatment personnel use a good memory, repair records, a large wall map and a hydraulic model of the larger transmission mains to help identify problem areas and maintain distribution system performance. A tool that is becoming increasing popular and affordable for many aspects of water utility management, including the tracking of main failures, is the microcomputer.

The objectives of this research were to: (a) identify pipe characteristics most likely to fail, (b) assess the resources necessary to utilize microcomputer in this application, (c) compare and contrast results with those of a previous study that only analyzed large transmission mains, and (d) evaluate the relevance of only analyzing a sample of a large utility compared to the time and cost necessary to study the entire network.

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Distribution system reliability for most utilities is maintained by the knowledge of a few key personnel. Generally, these water treatment personnel use a good memory, repair records, a large wall map and a hydraulic model of the larger transmission mains to help identify problem areas and maintain distribution system performance. A tool that is becoming increasingly popular and affordable for many aspects of water utility management, including the tracking of main failures, is the microcomputer.

In order to evaluate the feasibility of applying microcomputer technology to the assessment of distribution system reliability, a study was conducted in which a sample of the Cincinnati Water Works distribution network was analyzed. This study randomly selected a geographic cross-section of Cincinnati's distribution network accounting for approximately sixteen percent of the entire system mileage. All size mains in the selected areas were defined in a link/node format and merged with historical main break data and physical characteristics such as pipe type, soil type, pressure, age of main and diameter using a commercially available data base management system on an IBM PC/AT.

The objectives of this research were to: (a) identify pipe characteristics most likely to indicate potential failure in the system, (b) assess the resources necessary to utilize microcomputers in this application, (c) compare and contrast results with those of a previous study that only analyzed large transmission mains, and (d) evaluate the relevance of only analyzing a sample of a large utility compared to the time and cost necessary to study the entire network.

The purpose of this study was to present a tool useful to water utilities that not only could analyze historical data, but also provide a flexible and expandable mechanism for record-keeping enabling overall mangement of resources.

CASE STUDY AREA

The Cincinnati, Ohio Water Works (CWW) serves a population of over 3/4 million people. Both surface and groundwater sources are utilized to provide a maximum capacity of nearly 260 million gallons per day

(11.39 m^3/sec), with the Ohio River supplying the majority of the raw water. On a yearly average approximately 150 million gallons of water are pumped per day (6.51 m^3/sec). The distribution system consists of 2,500 miles (4022 km) of mains with the vast majority being cast iron.

In a previous analysis (1) the major transmission mains used in a hydraulic model for the entire CWW were studied. Many factors were found to influence the number of maintenance events associated with each pipe. Because only larger mains were studied, some of the conclusions may not be applicable systemwide. However, data were more readily available and the links and nodes already defined, thus making data collection less costly in time and money.

METHODOLOGY

The Cincinnati Water Works service area is covered by nearly 500 1 inch:200 feet scale maps. CWW personnel selected approximately ten percent of the maps they believed to present an accurate cross-section of the system. All size mains in the selected areas were defined in a link/node format and merged with historical main break data and physical characteristics such as pipe type, backfill material, pressure, age of main and diameter using a commercially available data base management system on an IBM PC/AT. A link was defined as a run of pipe between two nodes. A node was located at any tee, cross, change in diameter or installation date, end of main, or significant change in alignment, thus creating consistently shorter links than those used in hydraulic modeling. Detailed guidelines on geographic data base design and management discussed elsewhere (2,3) were utilized.

The IBM PC/AT included two floppy disk drives, a 10 megabyte hard disk, color monitor, 132 character printer and digitizer. The 1986 cost for a similar system and various software would be approximately $15,000. Repair data were collected from Repair Cards organized by street name. More detailed information has been collected by the CWW for approximately the past ten years on Underground Repair Cards containing data on cost, depth of main, internal and external pipe conditions found, and type of backfill material. Data collection, network identification, digitization of nodes and data entry if pursued on a daily basis would require 4-5 months effort for one person. A similar effort was required for the previous study analyzing the larger transmission mains. A major difference occurred in data entry and storage. The previous study used one large wall map to identify the network in colored pencil, and data were entered and stored on a mainframe computer. Timesharing and storage costs of such a large data base, depending on the particular situation, could cost well in excess of the hardware and software expenditures of the present study.

RESULTS

One of the objectives of the study was to compare characteristics of the sampled data to the entire distribution system as well as the results to other studies of entire systems. Figure 1 displays the pipes by diameter in the entire system, the hydraulic model and the sampled data set. The sampled data set corresponds to the actual system rather well compared to those in the hydraulic model.

There are 397 miles (639 km) of mains in the sampled data set, or approximately 16% of the entire system. There were 5,920 links with

an average length of 354 feet (108 m) in the sampled data set as compared to 400 links of an average length of 3,620 feet (1103 m) in the hydraulic modeling data set. The shorter lengths of pipe analyzed in this study resemble typical pipe repair and replacement efforts by utilities as well as reducing variability due to length that could confound more detailed statistical analyses. Of the 5,920 links, only 824 (or 14%) had any maintenance events. This fact agrees with previous studies (4,5) in Philadelphia, Pennsylvania and New Haven, Connecticut that found 19% and 21% of the links contained all the breaks respectively.

Repair data have been kept since 1940 at the Cincinnati Water Works. Table 1 exhibits repair event rates for a variety of utilities (5). The sampled data set is included in order to compare it with the entire system data. Only 1963-1984 Cincinnati data is included to cover comparable time periods for the sampled data set.

The data seem to indicate that the sampled data set for Cincinnati reflects results consistent with entire distribution systems. The high annual break rate for the sampled data set probably reflects a change in record keeping in Cincinnati during the past ten years, more so than a deteriorating system. The fact that the entire CWW distribution system had an average repair rate of 21.2/100 miles/year and a 4.9% average annual break rate increase indicate there may be some bias in the sampled data set toward problem areas.

Table 2 reports on the type of repair for some of the utilities mentioned along with the Cincinnati sample data set. Once again, the sample data set compares favorably with entire distribution systems.

The break type also varies by diameter of pipe. Figure 2 summarizes these results. Circumferential breaks are more prevalent on small diameter mains. As mains increase in diameter, circumferential breaks decrease while longitudinal breaks increase. Holes also occur more frequently on larger mains. In the sampled data set there were too few breaks on large mains to characterize their break type pattern. Joint repairs increase substantially and this could be due to CWW's use of leadite in the 1950's in certain areas. Numerous joint repairs and split bells can be attributed to a few specific mains in the distribution system which could also account for the increasing break rate since the CWW has essentially replaced those joints en masse.

Figure 3 presents a comparison of Cincinnati Water Works' break patterns by diameter. All utilities display a similar pattern of higher repair rates for the smaller diameter mains than the larger mains (5). Thus, analyzing only larger mains used in hydraulic modeling, which utilities may be tempted to do given the ease of data collection, may provide nonrepresentative results.

Seasonal repair patterns were also found. As expected, the colder winter months exhibited more maintenance events as displayed in Figure 4. Also displayed are data from the previous CWW study for larger mains. As can be seen the data differs greatly. This could reflect a difference in emergency vs. elective repair that can be left for better weather. An example of this was the systematic replacement throughout the summer months of leadlite joints that occurred in clusters.

PROBABILITY OF FAILURE ANALYSIS

In this study, the Cox Proportional Hazards Model is applied to estimate the pattern of breaks in time and the effects of variables on the break rate. The Cox Model (6,7) was developed for any type of data involving survival times. The model can take the form of:

$$Pr = \exp (b_1x_1+b_2x_2+.....b_nx_n)$$

where

Pr = Probability of breaking after time t given no breaks up to time t

b = coefficient of independent variables

x = independent variables.

An advantage of this technique is its ability to stratify data according to installation or manufacturing time periods or other pipe and environmental characteristics as necessary. Figure 5 demonstrates how the proportional hazards model can be used to identify those mains most likely to break. Mains with extremely high or low probabilities can be identified in order that those characteristics that influence pipe reliability can be assessed. Currently, manufacturing and installation techniques, pressure, length and diameter are being investigated.

CONCLUSIONS AND RECOMMENDATIONS

Various analyses of the sampled data set for the Cincinnati Water Works indicate that break rates, break types, breaks by diameter and season compare favorably with studies on entire distribution systems. Analyzing a subset of a utility only involving the larger transmission mains does not seem to reflect the entire system repair characteristics. Although, analysis of the larger mains is important in assessing those mains that could have a larger impact on property damage, fire safety or disruption of service to large segments of the system, a utility should at least sample all mains to obtain an accurate picture of the system.

In developing reliability analysis for distribution systems there are advantages to collecting only a subset of the entire network. The time and effort saved by only collecting 10% of the system is obvious. Collecting data for the entire CWW would require approximately 1.5 years of effort compared to .5 years for the sample. There would be simplifications doing the entire system since personnel would not have to deal with problems regarding which data to include in the sample. The sampled data can be entered, analyzed and stored on a microcomputer without expensive timesharing costs. Also, digitization of the network enables alternatives and spatial analysis of the network not possible with a large wall map.

Disadvantages of sampling the network and using a microcomputer are obviously the loss of information. The microcomputer is also limited in its storage capability, speed of analysis and statistical analyses. The IBM PC/AT could probably accommodate the entire CWW distribution system, but analysis would be very slow. Larger utilities may possess their own mainframes and the microcomputer could be used to enter and store the data and upload it as needed on the mainframe for analysis.

Developing reliability analyses for distribution systems should include all facilities including valves, hydrants, pumps, etc. in addition to the mains. Facility inventory data should include: (a) facility identification, (b) location description, (c) coordinates and (d) facility characteristics. In sampling all components of a distribution system, a utility can develop probabilities of failure for pumps of various size, age, manufacture, and power for example, assign these values system wide and develop models for availability and reliability.

This study has demonstrated, for at least the case study distribution system, that sampling can provide reasonable estimates for the entire system at a moderate level of effort. This effort enables quicker data collection and development of risk assessments for personnel managing a system with increasing probability of failure, with possible decreasing staff and funding.

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Table 1. Repair Rate Comparison

Utility	System Miles	Period	Average Repair Events/yr	Average* Repair Rate	*Annual Growth Rate % yr
Denver, CO	2,158	1976-1983	222	10.8	0
East Bay, CA	3,496	1973-1982	901	25.9	-4.0
Kenosha, WI	267	1974-1982	95	35.6	3.4
Louisville, KY	2,557	1963-1983	427	23.7	3.7
Philadelphia, PA	3,272	1964-1980	880	26.9	1.8
New York, NY	6,145	1970-1978	463	7.9	1.5
Cincinnati, OH	397*	1963-1984	66	16.6	8.8

*16% of system
**repairs/100 miles/year

Table 2. Percent of Total Repair by Part Damaged

Utility	Joint	Circum-ferential	Longi-tudinal	Hole/ Blowout	Other
East Bay, CA	25	19	12	22	22
Kenosha, WI	18	62	6	14	0
Cincinnati, OH	23	49	20	8	0

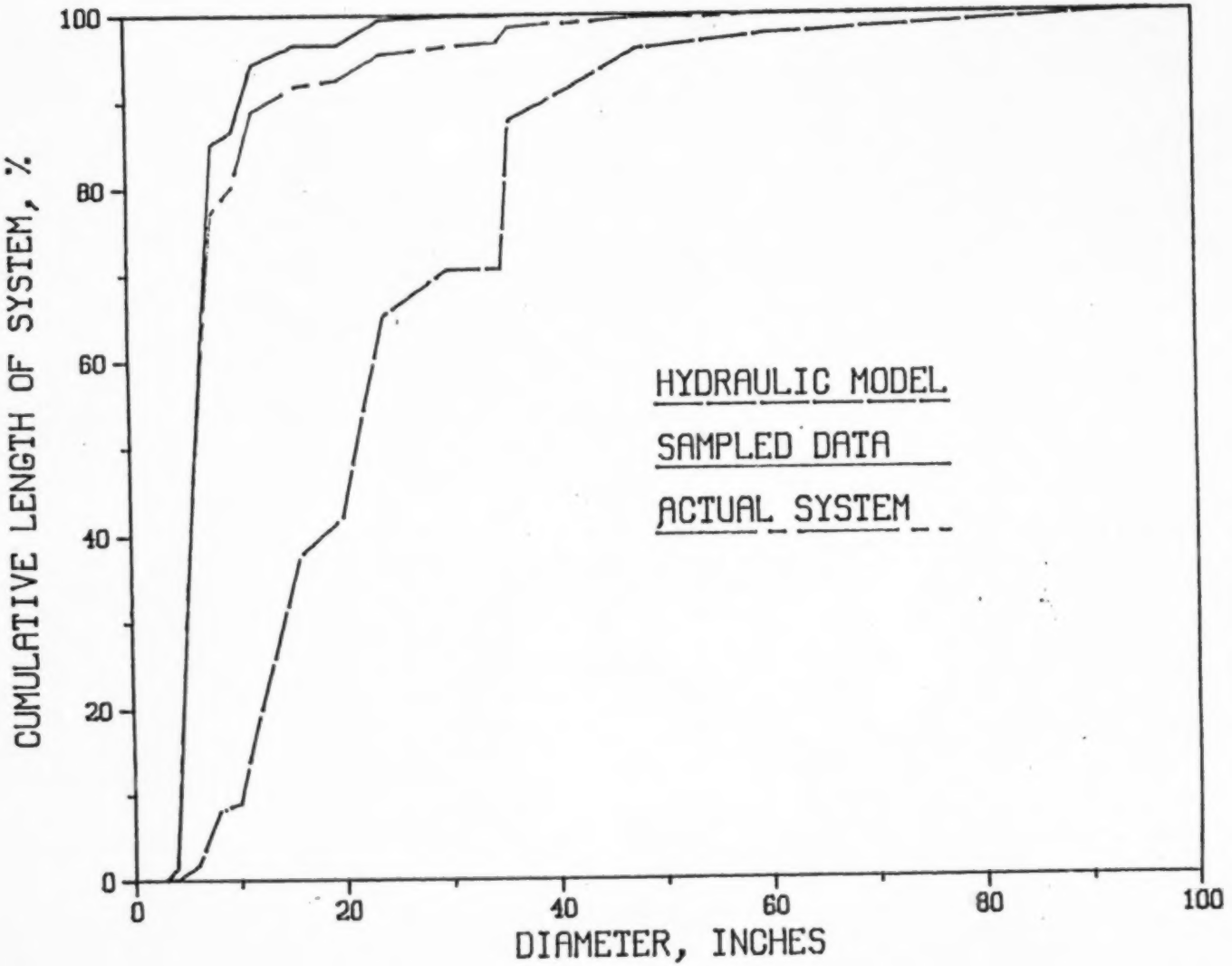

FIGURE 1. DISTRIBUTION SYSTEM CHARACTERISTICS

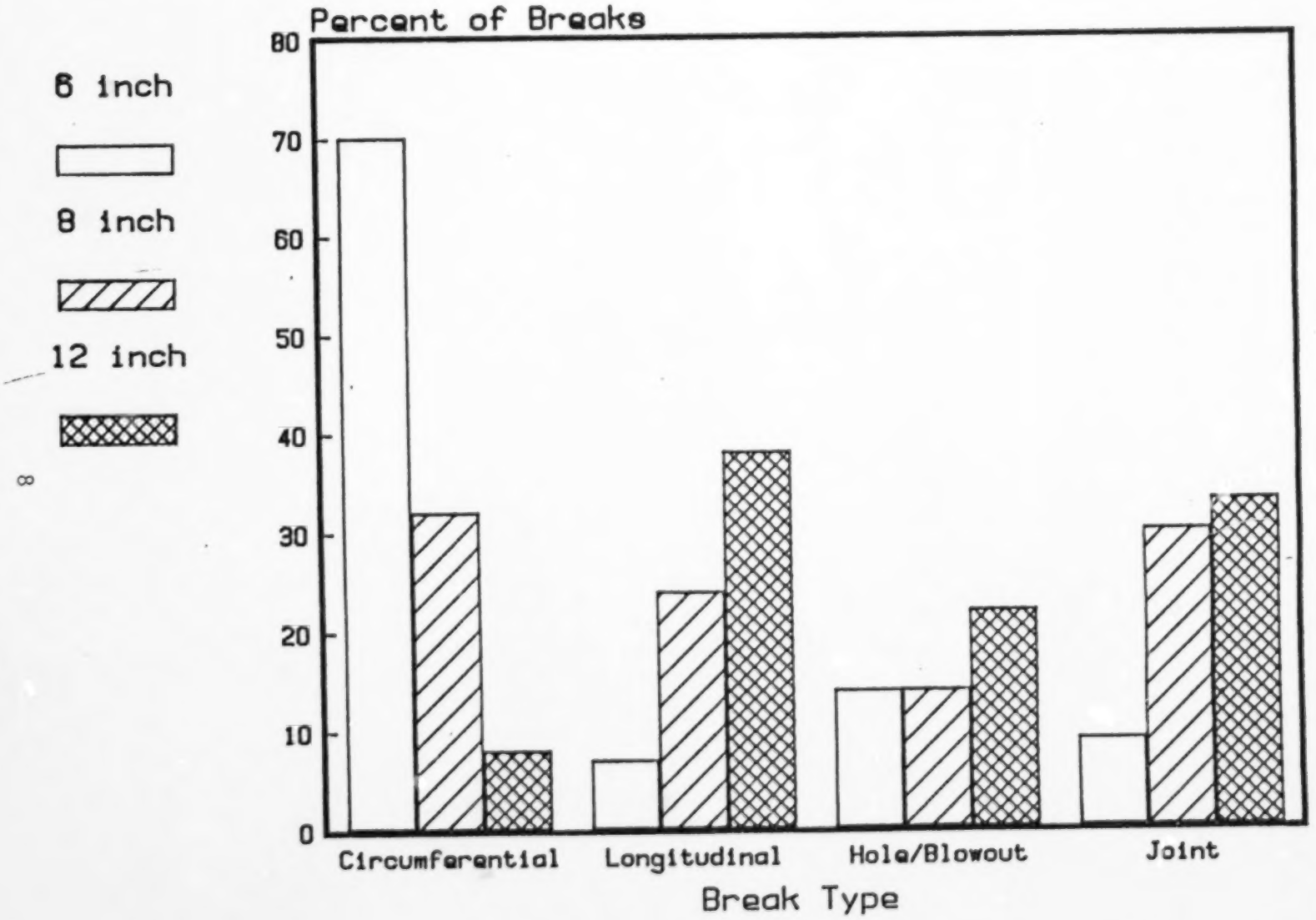

FIGURE 2. FREQUENCY OF PIPE BREAKS BY DIAMETER AND TYPE

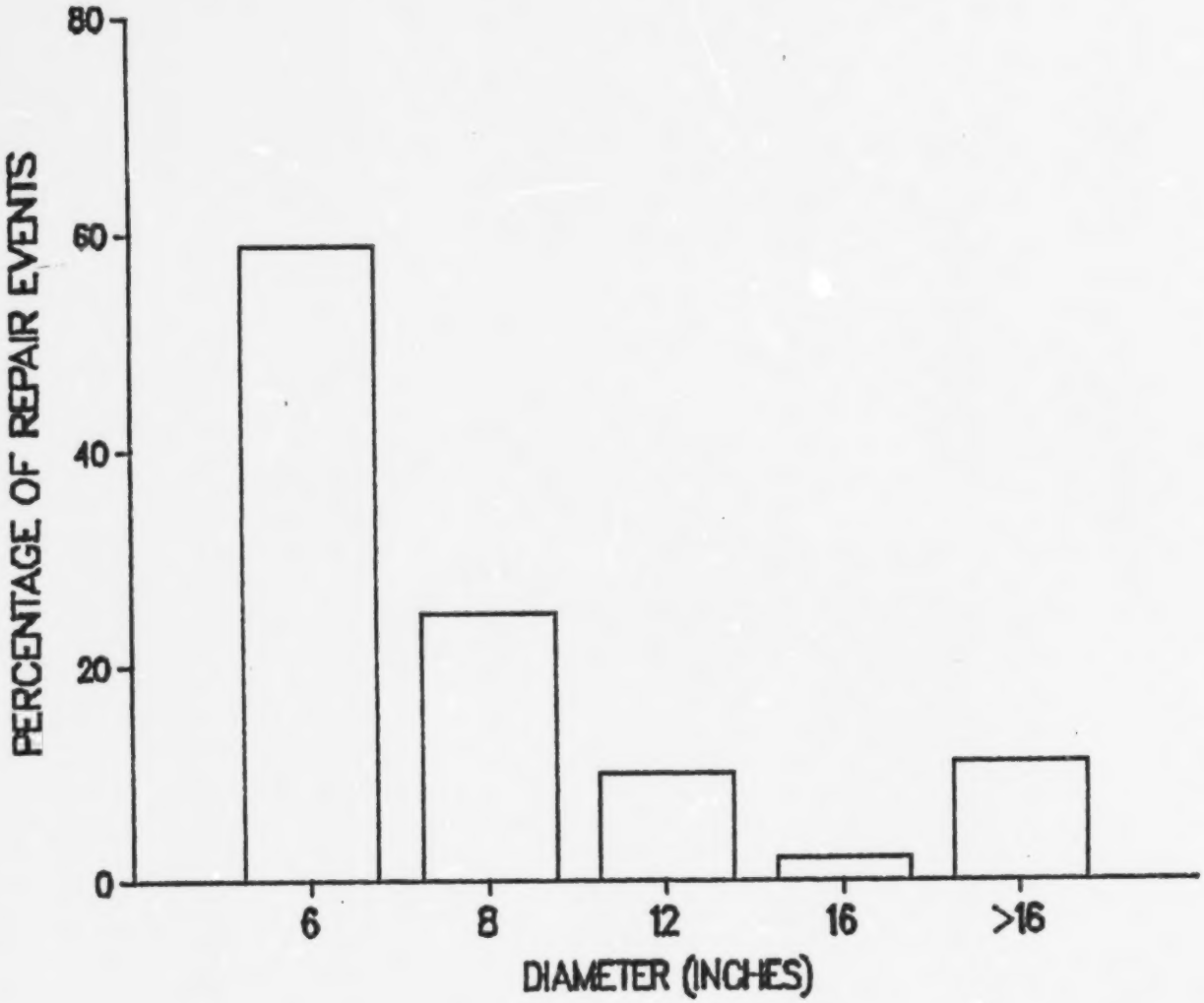

FIGURE 3. CINCINNATI WATER WORKS REPAIR RATE BY DIAMETER

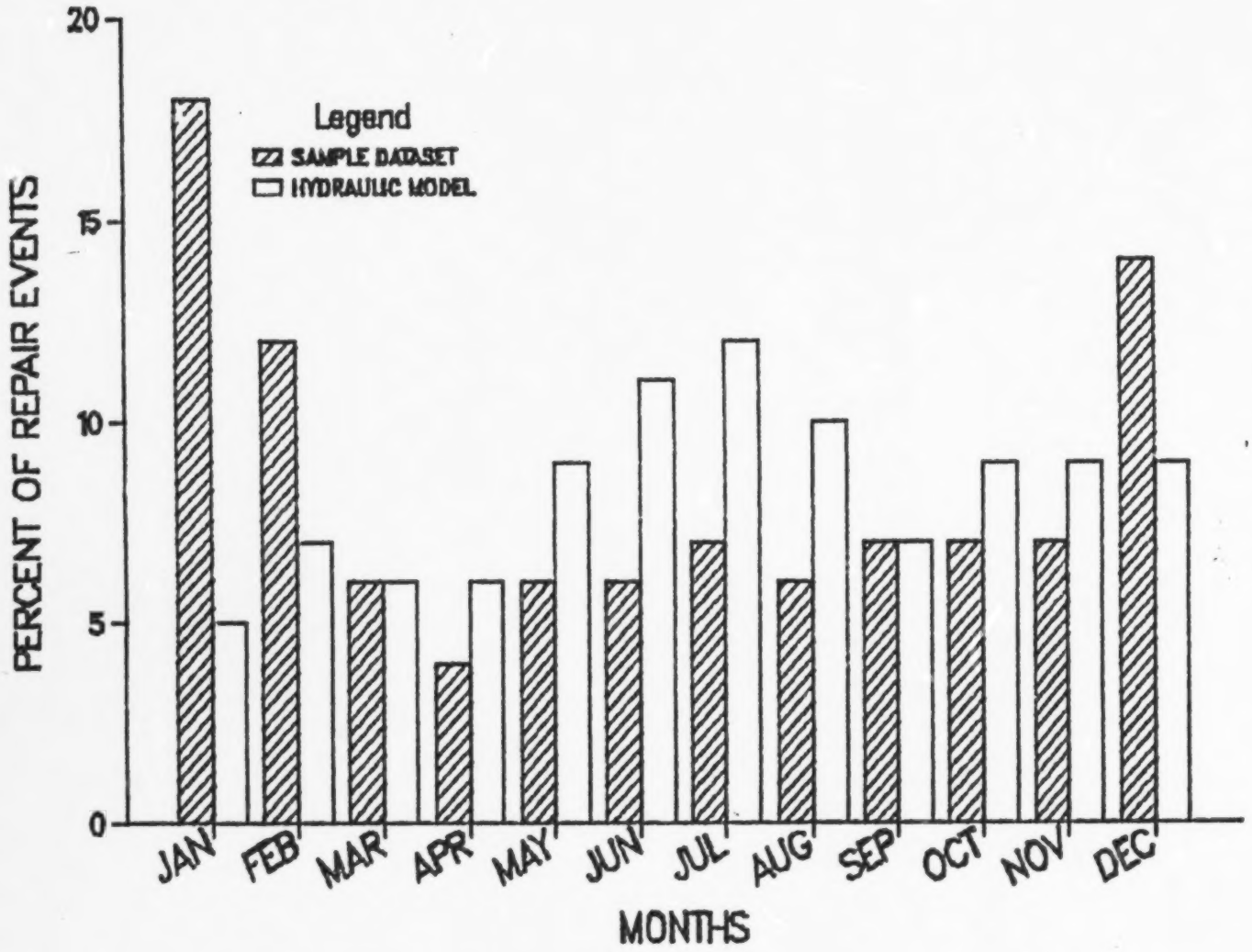

FIGURE 4. CINCINNATI WATER WORKS MONTHLY REPAIR RATE

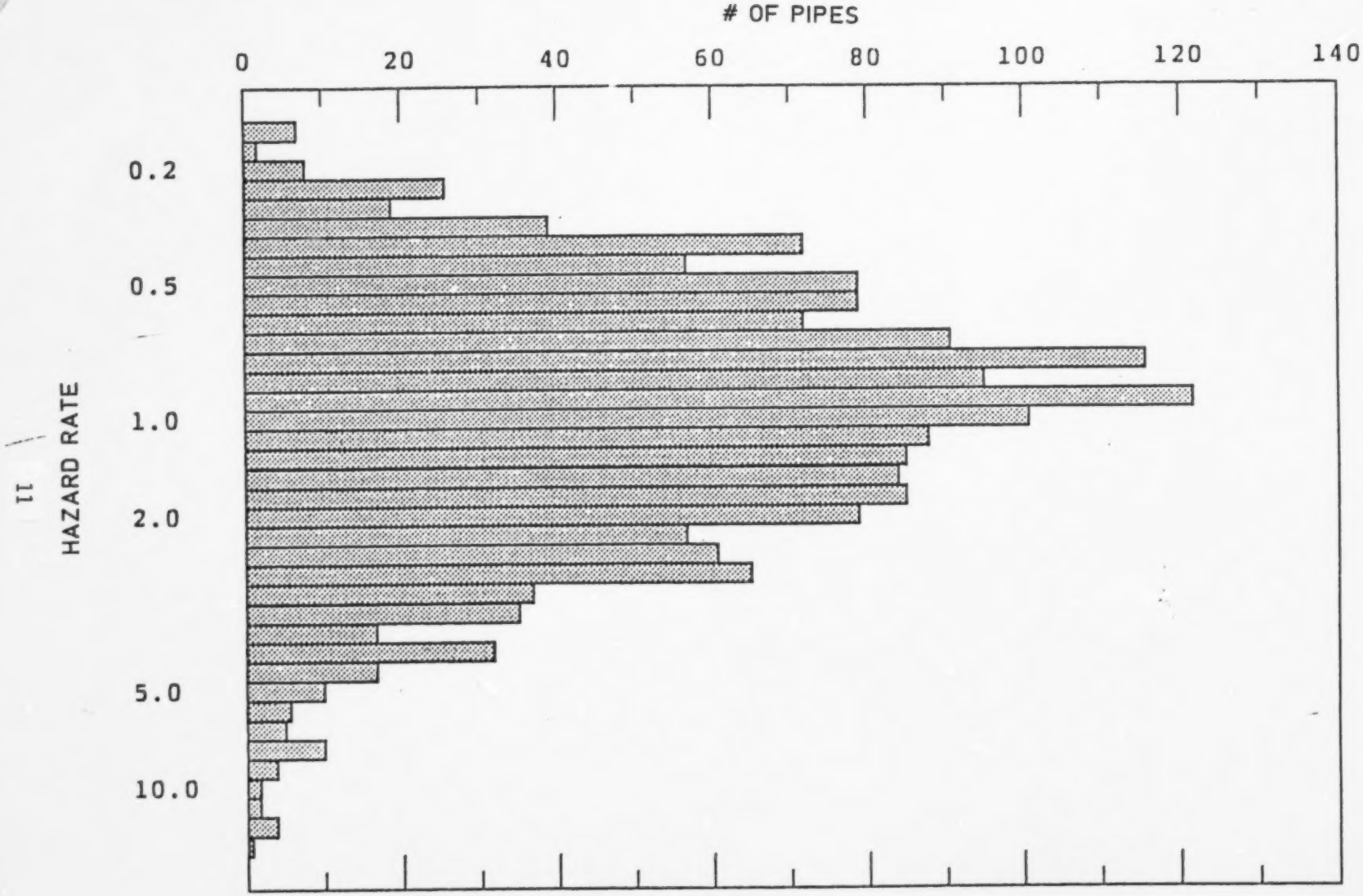

FIGURE 5. RELATIVE HAZARD RATE